

## HOT DUST OBSCURED GALAXIES WITH EXCESS BLUE LIGHT: DUAL AGN OR SINGLE AGN UNDER EXTREME CONDITIONS?

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## ABSTRACT

Hot Dust-Obscured Galaxies (Hot DOGs) are a population of hyper-luminous infrared galaxies identified by the WISE mission from their very red mid-IR colors, and characterized by hot dust temperatures ( $T > 60$  K). Several studies have shown clear evidence that the IR emission in these objects is powered by a highly dust-obscured AGN that shows close to Compton-thick absorption at X-ray wavelengths. Thanks to the high AGN obscuration, the host galaxy is easily observable, and has UV/optical colors usually consistent with those of a normal galaxy. Here we discuss a sub-population of 8 Hot DOGs that show enhanced rest-frame UV/optical emission. We discuss three scenarios that might explain the excess UV emission: (i) unobscured light leaked from the AGN by reflection over the dust or by partial coverage of the accretion disk; (ii) a second unobscured AGN in the system; or (iii) a luminous young starburst. X-ray observations can help discriminate between these scenarios. We study in detail the blue excess Hot DOG WISE J020446.13–050640.8, which was serendipitously observed by *Chandra*/ACIS-I for 174.5 ks. The X-ray spectrum is consistent with a single, hyper-luminous, highly absorbed AGN, and is strongly inconsistent with the presence of a secondary unobscured AGN. Based on this, we argue that the excess blue emission in this object is most likely either due to reflection or a co-eval starburst. We favor the reflection scenario as the unobscured star-formation rate needed to power the UV/optical emission would be  $\gtrsim 1000 M_{\odot} \text{ yr}^{-1}$ . Deep polarimetry observations could confirm the reflection hypothesis.

**Keywords:** galaxies: active — galaxies: evolution — galaxies: high-redshift — quasars: general — infrared: galaxies

## 1. INTRODUCTION

The most luminous infrared (IR) galaxies in the universe are thought to be massive galaxies during a key stage in their evolution (see, e.g., Hopkins et al. 2008). These galaxies are undergoing a combination of intense star-formation and intense accretion onto their central super-massive black hole (SMBH), in both cases heavily enshrouded in dust. This makes these objects exceedingly luminous in the IR but typically faint at UV/optical wavelengths. There are several populations of galaxies that are known to be in such stages,

both locally, such as Ultra-Luminous Infrared Galaxies (ULIRGs; e.g., Sanders & Mirabel 1996), and at high- $z$ , such as Submillimeter Galaxies (SMGs; Blain et al. 2002; Casey et al. 2014), Dust-Obscured Galaxies (DOGs; Dey et al. 2008) and Hot Dust-Obscured Galaxies (Hot DOGs; Eisenhardt et al. 2012; Wu et al. 2012), the latter of which were recently discovered by NASA’s Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010).

Hot DOGs have characteristics that clearly separate them from other populations of luminous galaxies. One of their most distinctive properties is the hot dust temperatures from which the population draws its name (see Wu et al. 2012). Objects such as ULIRGs and SMGs have IR spectral energy distributions (SEDs) that peak at  $\lambda \sim 100 \mu\text{m}$  and have typical dust temperatures of up to  $\sim 40$  K (e.g., Blain et al. 2003; Magnelli et al. 2012). This is consistent with their IR luminosities being powered primarily by star-formation. DOGs can have somewhat warmer dust temperatures, as they are powered by a combination of Active Galactic Nuclei (AGN) and star-formation (Melbourne et al. 2012). Hot DOGs have much hotter dust temperatures of  $T > 60$  K (Wu et al. 2012), with shoulders to their SEDs of far-IR emission very significantly broader than single-temperature modified black-bodies, and with dust components with temperatures up to  $\sim 450$  K (Eisenhardt et al. 2012; Tsai et al. 2015). Because of these high temperatures, their SEDs peak at rest  $\lambda \sim 20 \mu\text{m}$ , suggesting they are powered by extremely luminous, highly obscured Active Galactic Nuclei (AGN).

Although the redshift distribution of Hot DOGs is similar to that of DOGs and SMGs, with most objects

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found at  $1 < z < 4$  (Assef et al. 2015; Eisenhardt et al. in prep.), their luminosities are significantly larger. Almost all Hot DOGs seem to have luminosities exceeding  $L_{\text{IR}}(8 - 1000\mu\text{m}) = 10^{13} L_{\odot}$  (Tsai et al. 2015), placing them in the category of Hyper-Luminous Infrared Galaxies (HyLIRGs,  $L_{\text{IR}} > 10^{13} L_{\odot}$ ). Indeed, a significant fraction have  $L_{\text{IR}} > 10^{14} L_{\odot}$  (Wu et al. 2012), making them Extremely Luminous Infrared Galaxies (ELIRGs,  $L_{\text{IR}} > 10^{14} L_{\odot}$ ; Tsai et al. 2015). Hot DOGs rank among the most-luminous galaxies known (Tsai et al. 2015). In fact, Hot DOG W2246–0526 is the most luminous galaxy currently known (Tsai et al. 2015; Diaz-Santos et al. 2015). As expected for such objects, Hot DOGs are a rare population, with WISE only identifying one candidate every  $\sim 30 \text{ deg}^2$  (Eisenhardt et al. 2012; Wu et al. 2012; Assef et al. 2015), with space densities comparable to those of similarly luminous QSOs (Assef et al. 2015). Hot DOGs also reside in significantly overdense environments (Jones et al. 2014; Assef et al. 2015) and a large fraction show extended Ly $\alpha$  emission features on scales of up to  $\sim 100 \text{ kpc}$  (Bridge et al. 2013).

The very red rest-frame optical through mid-IR SEDs of Hot DOGs imply that the hyper-luminous AGN that powers the IR is under significant obscuration ( $\langle E(B - V) \rangle = 6.4$ , up to  $E(B - V) \sim 20$ ; Assef et al. 2015), enough that the rest-frame UV-through-NIR SED is dominated by the underlying stellar emission, providing an uncompromised view of the host galaxy. Using *Spitzer* and ground-based NIR follow-up imaging observations to constrain the host-galaxy properties, Assef et al. (2015) studied their stellar masses and determined upper bounds of  $M_{\star} \lesssim 10^{12} M_{\odot}$ . They also showed this result is supported by the density of their environments as measured from *Spitzer* follow-up imaging (see Assef et al. 2015, for details). Although Hot DOG host galaxies may be among the most massive ones at their redshifts, the AGN is still unexpectedly luminous. Assef et al. (2015) show that in order to explain the AGN activity, it is necessary that either the SMBH is overly massive for its host galaxy or that the AGN is radiating significantly above the Eddington limit, or possibly a combination of both. The super-Eddington accretion scenario is also supported by the study of the most luminous Hot DOGs ( $L_{\text{IR}} > 10^{14} L_{\odot}$ ) conducted by Tsai et al. (2015).

Being able to directly probe the host galaxy of these objects can also allow us to understand their rest-frame UV/optical properties. Previous studies of the SEDs of Hot DOGs have shown that most are well modeled by a regular star-forming galaxy at these wavelengths (see Eisenhardt et al. 2012; Assef et al. 2015, as well as §2). In this work, however, we focus on a small fraction of them that show exceedingly blue UV/optical SEDs. When modeling the SEDs of these Hot DOGs with excess blue emission, we find with a significant probability that a type 1 AGN is needed to explain the blue rest-frame colors, but with a bolometric luminosity that is  $\sim 1\%$  of that of the highly obscured AGN powering the hyper-luminous IR emission. These uncommon sources may provide important insights into the nature of the Hot DOG population and their role in the galaxy evolution paradigm. X-ray observations can provide key tests of explanations for them. As Hot DOGs are typically

faint in soft X-rays, due to the large, possibly Compton-thick, absorbing H I column density (Stern et al. 2014; Piconcelli et al. 2015), deep X-ray observations are required to carry out such tests.

One of these uncommon sources, WISE J020446.13–050640.8 (W0204–0506 hereon) is located in the NOAO Deep Wide-Field Survey (Jannuzi & Dey 1999, ND-WFS) Cetus field, within the footprint of the Large-Area Lyman Alpha survey (LALA; Rhoads et al. 2000), which has been observed to a depth of 174.5 ks by the *Chandra X-ray Observatory* with the ACIS-I instrument (Wang et al. 2007). This makes W0204–0506 the Hot DOG with the deepest X-ray observations to date. We use these X-ray observations in combination with multi-wavelength data to study W0204–0506. In §2 we discuss the selection and possible nature of objects with blue excess emission in general, while in §3 we focus on the UV through mid-IR SED of W0204–0506. In §4 we discuss the *Chandra* observations, and in §5 we discuss the nature of W0204–0506. Throughout this work we assume a flat  $\Lambda$ CDM cosmology with  $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_{\Lambda} = 0.7$ . We refer to all magnitudes in their standard photometric system, namely AB for *griz* and Vega for all other bands.

## 2. BLUE EXCESS HOT DOGS

As discussed earlier, the fact that the AGN powering the IR emission of Hot DOGs is under heavy dust obscuration allows for the possibility of studying in depth the underlying host galaxy. The rest-frame UV through NIR SED of a galaxy can provide interesting constraints on the underlying stellar population, such as its age and mass, as well as the unobscured star-formation rate (e.g., Kennicutt 1998) and the star formation history. Eisenhardt et al. (2012) showed that the first Hot DOG studied in depth, WISE J181417.29+341224.9, had an SED dominated by a strongly star-forming galaxy ( $\sim 300 M_{\odot} \text{ yr}^{-1}$ ) at  $\lambda_{\text{rest}} \lesssim 1 \mu\text{m}$ . This is consistent with the fact that this object has a rest-frame UV spectrum similar to a Lyman break galaxy, with no discernible emission lines other than Ly $\alpha$ , and several interstellar absorption lines typical of the Lyman break population (e.g., Shapley et al. 2003). Wu et al. (2012) showed that although a fraction of Hot DOGs have similar rest-frame UV spectra, most show high-ionization narrow emission lines indicative of type 2 AGN and a small subset even show broad emission lines such as C IV. The expectation is, then, that these objects have a significant range of rest-frame UV through NIR SEDs.

To study their SEDs we rely here on the subset of sources with photometry provided by the Sloan Digital Sky Survey (SDSS; York et al. 2000). Note that although Hot DOGs are selected over the entire extragalactic sky, they are typically faint in the optical, with  $r \gtrsim 23$ . This implies that although a significant fraction of our objects lie within the SDSS footprint, only a fraction are detected. Specifically we find that 433 out of 934 Hot DOG candidates fall within the area covered by SDSS DR12 (Ahn et al. 2014), of which 153 (35%) are detected with  $S/N \geq 3$  in at least one band and 114 are detected at the same level in at least three passbands. To complement this, we use the NIR imaging from Assef et al. (2015) and the deeper *r*-band observations from the Hot DOG imaging program presented by Eisenhardt et al.

(in prep.). A brief description of the latter is also provided by Assef et al. (2015).

Assef et al. (2015, also see Eisenhardt et al. 2012) recently studied the rest-frame optical through mid-IR SEDs of a large sample of Hot DOGs, and showed that the combination of a composite host galaxy SED template and a single obscured AGN SED template typically does a good job of modeling the photometry. Assef et al. (2015) model their SEDs using the algorithm and templates of Assef et al. (2010). The best-fit SED models consist of a non-negative combination of three empirically derived galaxy templates, approximately corresponding to E, Sbc and Im type galaxies, and a single AGN template. They also fit for the reddening of the AGN component, parametrized by the color excess  $E(B - V)$ , considering values from 0 to  $10^{1.5}$ . The assumed reddening-law corresponds to an SMC-like extinction for  $\lambda < 3300\text{\AA}$ , and a Galactic extinction curve at longer wavelengths. Additional details are provided in Assef et al. (2010, 2015). From here on we will refer to this SED model as the “1AGN” model, as a single AGN component is used. Assef et al. (2015) modeled the SED of 96 Hot DOGs with spectroscopic redshifts  $z > 1$  and for which follow-up imaging had been obtained by *Spitzer* (Griffith et al. 2012), using WISE W3 and W4 bands from the WISE All-sky data release (Cutri et al. 2012), [3.6] and [4.5] imaging from the *Spitzer* follow-up, and *J*, *H* and *Ks* imaging from the NIR follow-up program presented by Assef et al. (2015) whenever available. The suggested correction to the WISE W3 and W4 band photometry for red sources by Wright et al. (2010, also see Brown et al. 2014) was applied before modeling the SEDs.

Here, we recalculate these fits but modify the sample to encompass only the 36 Hot DOGs with a)  $z > 1$  (following Assef et al. 2015) and b) available *ugriz modelMag*<sup>12</sup> photometry in the SDSS DR12 database with  $S/N > 3$  in at least one band. Note that of these, 28 have  $S/N \geq 3$  in at least three SDSS bands. Unlike Assef et al. (2015), we also consider here Hot DOGs not covered by the *Spitzer* follow-up program, using for them the lower  $S/N$  W1 and W2 fluxes from the AllWISE data release (Cutri et al. 2013)<sup>13</sup> instead. We note that Assef et al. (2015) decided to not use AllWISE fluxes due to concerns over the selection function modeling, but these are not important for our current study. Additionally, we add the *r*-band photometry from the follow-up program described by Eisenhardt et al. (in prep.) for 25 sources.

When including the observed optical photometry we find that the “1AGN” model no longer provides a good fit for a fraction of Hot DOGs which present significant excess emission at rest-frame UV/optical wavelengths compared to what is allowed by the SED templates of Assef et al. (2010). This excess is similar to what would be expected from an unobscured AGN, although much

**Table 1**  
Blue Excess Hot DOGs

WISE ID	Redshift	W4 (mag)	$P_{\text{ran}}(10^{-2})$
WISE J001926.88–104633.3	1.641	7.08	3.3
WISE J020446.13–050640.8	2.100	7.06	4.5
WISE J022052.12+013711.6	3.122	7.08	0.2
WISE J083153.25+014010.8	3.912	7.28	1.5
WISE J105045.92+401359.1	1.987	7.08	2.7
WISE J131628.53+351235.1	1.956	7.02	2.8
WISE J153550.03+310054.9	1.921	6.86	2.8
WISE J162101.29+254238.3	2.725	7.66	2.4

**Note.** — The W4 magnitudes presented here correspond to the values reported in the All-Sky catalog, uncorrected by the Wright et al. (2010) prescription.

less luminous than the one powering the IR emission. To properly identify these sources, we refit all 36 objects in our sample using the same algorithm described earlier, but adding an additional AGN component with the same template for which we fit an independent normalization and reddening value. We refer to this SED model as the “2AGN” model. Note that the “1AGN” and “2AGN” models have four and six parameters, respectively. An F-test shows that 8 of the 36 sources (22%) have good fits and a probability ( $P_{\text{ran}}$ ) below 5% that the improvement due to the additional AGN component is spurious. These sources are shown in Table 1<sup>14</sup>. The four sources with the highest probability of needing a secondary AGN component are shown, as examples, in Figure 1. The rest-frame UV optical emission is clearly consistent with that of a type 1 AGN. Because of their significant excess rest-frame UV/optical emission, we refer to these objects as Blue Excess Hot DOGs (BHDs).

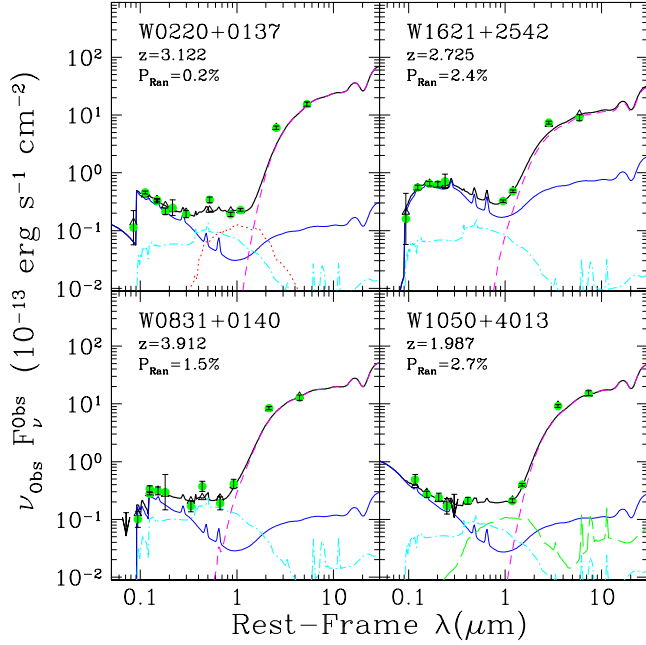
While  $P_{\text{ran}} = 5\%$  could be considered a large enough probability to be wary of the F-test interpretation, we note that the constraints on the presence of the secondary AGN are much tighter, as the F-test cannot take into account the fact that the non-negative requirement for the combination of our templates provides additional constraints. In order to further assess the need for the secondary AGN component in the best-fit SED model of these objects, we have created 1,000 realizations of their observed SEDs by re-sampling the photometry according to its uncertainties. We find that the secondary AGN component is needed (which we define as the best-fit secondary AGN component providing at least 2/3 of the flux in one or more of the SDSS bands) in 98% of the realizations. For comparison, objects with  $P_{\text{ran}} > 30\%$  use the secondary AGN component in only 66% of the realizations.

Determining the fraction of Hot DOGs that show this blue excess is challenging given the selection effects. As

<sup>14</sup> An additional source (WISE J085929.94+482302.3) has  $P_{\text{ran}} = 0.034$ , but we consider the fit to be unreliable. In particular, SDSS reports an *r*-band *modelmag* flux for this object that differs by over an order of magnitude from that measured in a  $3''$  aperture (*fibermag*), and provides a warning of unreliable photometry. The  $3''$  aperture reported by SDSS is consistent with the flux we measure in a slightly larger  $4''$  aperture in deep *r*-band imaging we have obtained from the WIYN 3m telescope, and we can confirm the object is marginally resolved within the  $0.85''$  PSF of these observations. This suggests the *modelmag* fluxes reported in the SDSS are unreliable for this object and hence we do not consider it further in our analysis.

<sup>12</sup> [http://www.sdss.org/dr12/algorithms/magnitudes/#mag\\_model](http://www.sdss.org/dr12/algorithms/magnitudes/#mag_model)

<sup>13</sup> Note that the bias to underestimate the flux in the WISE W1 and W2 bands reported by Lake et al. (2013) for the All-sky data release has been fixed in the AllWISE data release. Also note that approximately 1% of Hot DOG candidates are not formally detected in the AllWISE catalog, possibly because they are confused with fast moving sources. For those, when no *Spitzer* data is available, we use the All-Sky W1 and W2 fluxes corrected for the bias reported by Lake et al. (2013).



**Figure 1.** SEDs of the four Hot DOGs with the lowest probability  $P_{\text{Ran}}$  that the improvement in  $\chi^2$  gained from adding the secondary AGN component is spurious. The green solid points show the observed flux densities in a combination of the  $u'$ ,  $g$ ,  $r$ ,  $i$ ,  $z$ ,  $J$ ,  $H$ ,  $Ks$ , *Spitzer* and WISE bands (not all bands available for all targets, see §2 for details). The best-fit SED model (solid black line) consists of a non-negative linear combination of a primary luminous, obscured AGN (dashed magenta line), a secondary less luminous, unobscured or mildly obscured AGN (solid blue line), an old stellar population (dotted red line), an intermediate stellar population (dashed green line, not needed for all the objects presented here) and a young stellar population (cyan dotted-dashed line). Note that not all host galaxy templates are used by the algorithm to model the SED of each object. The open triangles show the flux density of each photometric band predicted by the best-fit SED model.

discussed by Assef et al. (2015), the spectroscopic follow-up program has mostly focused on the brightest objects in W4, namely the 252 Hot DOG candidates with  $W4 < 7.2$ . Of the 36 objects in our sample, 22 fall in this category and 6 are selected as BHDs. However, there is a strong bias for BHDs to be detected by SDSS so we instead need to consider all objects within the SDSS area to assess their true fraction. There are 51 Hot DOGs with  $z > 1$  and  $W4 < 7.2$  within the SDSS DR12 area. As this sample is limited by W4, we posit that objects that are faint at observed optical wavelengths, and hence reddest in optical-W4, are unlikely to have blue excesses, and, in turn, be classified as BHDs. While this is likely a reasonable assumption, this is not guaranteed since the BHD selection criteria is based primarily on the UV/optical SED shape, and further observations are needed to properly assess this. Regardless, assuming that SDSS undetected Hot DOGs are not BHDs implies a true fraction of 6/51 (12%). However there is a natural bias towards a higher success rate in measuring redshifts for the optically brighter objects. Considering that 30% of objects did not successfully yield a spectroscopic redshift (Assef et al. 2015; Eisenhardt et al. in prep.) and that these are unlikely to be BHDs for the same reason as discussed above, this implies that the true fraction is

closer to 6/73, or about 8% in the  $W4 < 7.2$  sample. Extrapolating this to the entire Hot DOG sample at fainter W4 is not trivial due to the observational biases discussed. We note that only 2 BHDs are identified among Hot DOGs with  $W4 > 7.2$ , suggesting the true fraction of BHDs might be significantly lower when considering the entire population.

We suggest three potential scenarios to explain these BHDs.

*Leaked AGN Light:* A single AGN is present in the system and is responsible for the IR emission by heating the dust that surrounds it in almost all directions. However, a small fraction of the rest-frame optical/UV emission of this luminous AGN is leaked out of the high-obscuration region. One possibility is that a fraction of the AGN light is scattered off into our line of sight. This effect has been observed in local Seyfert 2 galaxies through polarimetry (Antonucci & Miller 1985; Antonucci 1993), and the AGN powering the IR emission in Hot DOGs may be luminous enough for its scattered component to dominate the rest-frame UV/optical fluxes. Alternatively, a small opening between the dust clouds may allow us a partial direct line of sight towards the accretion disk. The opening would have to be small enough that only  $\sim 1\%$  of the accretion disk is directly visible. While in these scenarios one would naively expect to see other targets with partially obscured UV AGN emission, the SED selection method would not be able to identify them as it is only sensitive to those with the largest UV excesses.

*Dual Quasar:* The secondary AGN emission component may come from an additional accreting SMBH in the system that is much less luminous than the highly obscured one powering the IR emission. Since major mergers are thought to play an important role in the evolution of massive galaxies and, in particular, in the triggering of intense, obscured AGN and star-formation activity (see, e.g., Hopkins et al. 2008; Koss et al. 2011a), Hot DOGs could correspond to merger stages during which the SMBHs are not yet gravitationally bound (e.g. Comerford et al. 2009). The combination of a dual AGN with a luminous, obscured component and a less luminous but unobscured one has been previously observed in one candidate and one confirmed dual AGN, studied respectively by Barrows et al. (2012) and Fu et al. (2011), although the disparity between the component luminosities was much smaller than for BHDs. Because dust is likely abundant in Hot DOGs even on large scales, we expect the scenario in which only one nucleus is unobscured to be more likely if the nuclei are separated by scales  $\gtrsim 1$  kpc, as this is the typical size of the dusty region in ULIRGs (Díaz-Santos et al. 2011).

*Extreme Star Formation:* Alternatively, enhanced UV/optical emission could be produced by a young, massive starburst. A young starburst can have a broad-band power-law shaped SED, similar to that of an accretion disk, in the UV/optical regime (see,

e.g. Leitherer et al. 1999). The star-formation rate (SFR) needed to power such a luminous emission through a young starburst would be very substantial. Such an intense starburst would be coeval with a hyper-luminous obscured quasar, with important implications for galaxy evolution scenarios.

Additional observations can help disentangle some of these scenarios. For example, light leaked from the hyper-luminous AGN through reflection on the dust grains could be directly probed through spectropolarimetry, as the characteristic broad emission lines of type 1 AGN should be more apparent in polarized light (Antonucci & Miller 1985; Antonucci 1993). A young coeval starburst could be excluded through optical variability, as this would only be expected for light from an accretion disk. Furthermore, since the typical amplitude of the variability for a given timescale correlates with the accretion disk luminosity (Vanden Berk et al. 2004; MacLeod et al. 2010), long-term variability monitoring could allow us to differentiate whether the excess blue emission light is due to light leaked from the hyper-luminous AGN or comes from a secondary, lower luminosity active SMBH. Also, high spatial resolution UV/optical imaging could identify the two nuclei of a dual AGN, or confirm the presence of a galaxy-wide massive young starburst. The latter might also be probed by high resolution ALMA observations of the far-IR continuum and CO emission.

X-ray observations can also help test these scenarios. Stern et al. (2014) reported on combined *NuSTAR* and *XMM-Newton* observations of three Hot DOGs without blue excesses, showing that they have heavily absorbed (possibly Compton-thick) X-ray emission. If BHDs are due to partial coverage or a secondary unobscured accreting SMBH, we would expect commensurate unabsorbed X-ray emission coming from the fainter AGN component. On the other hand, if the excess rest-frame UV/optical were due to scattered light from the hyper-luminous, obscured AGN or from extreme star-formation, we would only expect to see strongly absorbed X-ray emission from the highly obscured AGN powering the infrared emission as X-ray photons are less scattered by dust grains or free electrons than UV ones. In principle very deep X-ray observations can also test the star-formation scenario through a significant soft X-ray excess (see Mineo et al. 2014, and §5.3).

As mentioned in §1, one of the Hot DOGs that we have identified as BHDs, namely W0204–0506, is located in the NDWFS Cetus field, within an area observed by the *Chandra X-ray Observatory* ACIS-I instrument. In the following sections we study its X-ray-through-IR SED to gain more insight into its nature, which may also help provide insight into the nature of excess blue light from the other BHDs.

### 3. THE UV THROUGH MID-IR SED OF W0204–0506

#### 3.1. Observations

W0204–0506 was selected as a Hot DOG candidate through the criteria of Eisenhardt et al. (2012). These candidates (or “W12-Drops”) are selected purely by their WISE magnitudes, corresponding to objects with  $W1 > 17.4$  mag, high  $S/N$  detections in either  $W3$  or  $W4$ , and with very red  $W2$ – $W3$  or  $W2$ – $W4$  colors (see

Eisenhardt et al. 2012, for details). Table 2 shows the WISE fluxes for W0204–0506 from the AllWISE Data Release.

By selection, Hot DOGs have low  $S/N$   $W1$  and  $W2$  fluxes. These wavelengths, however, provide significant information about the host, and hence are crucial for modeling the SEDs of these sources. To this end, we obtained *Spitzer* imaging of W0204–0506 in the  $[3.6]$  and  $[4.5]$  bands on UT 2011 February 28, as part of a comprehensive survey of the Hot DOG population (Griffith et al. 2012). We also obtained  $J$ -band imaging of W0204–0506 using the WHIRC camera on the WIYN telescope on the night of UT 2012 January 1 as part of the NIR follow-up campaign (Assef et al. 2015). Although optical photometry is available for this source from SDSS DR12 and the follow-up program mentioned in the previous section, we use instead deeper  $g'r'i'z'$  imaging obtained by Finkelstein et al. (2007) using the Multiple Mirror Telescope/Megacam in 2005 November and 2006 January. The fluxes of all these bands are listed in Table 2. The profile of this object is dominated by a central point source but shows an extended component that accounts for up to 30% of the integrated flux. We note that all three measurements of  $r$ -band photometry are consistent within the error-bars, so we cannot attempt to use optical variability to test the proposed scenarios (see §2). Table 2 also shows the fluxes of W0204–0506 in the *Herschel*/PACS  $70\mu\text{m}$  and  $170\mu\text{m}$  bands and in the *Herschel*/SPIRE 250, 350 and  $500\mu\text{m}$  bands, obtained as part of a Hot DOG follow-up program (PID: OT2<sub>peisenha\_2</sub>, PI: Eisenhardt; see Tsai et al. 2015, for details).

An optical spectrum of W0204–0506 was obtained with the GMOS-S spectrograph on the Gemini South telescope on UT 2011 November 27, using the  $1.5'' \times 108''$  longslit and the B600\_G5323 disperser with a  $2 \times 600$ s exposure time as part of an optical spectroscopic follow-up campaign of Hot DOGs (Eisenhardt et al. in prep.). Figure 2 shows the reduced spectrum of W0204–0506, which displays the C IV  $\lambda 1549\text{\AA}$ , He II  $\lambda 1640\text{\AA}$  and C III]  $\lambda 1909\text{\AA}$  emission lines at a redshift of  $z = 2.100 \pm 0.002$ . Each of the three emission lines is statistically well modeled by a single Gaussian component given the  $S/N$  of our observations. For C IV, He II and C III] we find that the best-fit Gaussian components have rest-frame FWHM of  $1630 \pm 220$ ,  $950 \pm 200$  and  $550 \pm 100 \text{ km s}^{-1}$  respectively. Note that the He II emission line is comparable in strength to C IV and C III], which is atypical of broad-lined quasars. For example, in the SDSS composite quasar spectrum of Vanden Berk et al. (2001), He II has 2–3% the strength of C IV and C III] though the comparison is unfair since He II is narrow and the carbon lines are dominated by broad emission in unobscured sources. For high luminosity narrow-line AGN such as radio galaxies, He II is often comparable in strength to the carbon lines, as seen in the composite radio galaxy spectra of McCarthy (1993) and Stern et al. (1999). Furthermore, the FWHM we find for C IV and He II are consistent with those measured in the composite spectrum of Stern et al. (1999, respectively  $1540$  and  $1150 \text{ km s}^{-1}$ ), although C III] is significantly narrower than the  $1260 \text{ km s}^{-1}$  found by Stern et al. (1999). As another example of the similarities between Hot DOGs and radio galaxies,

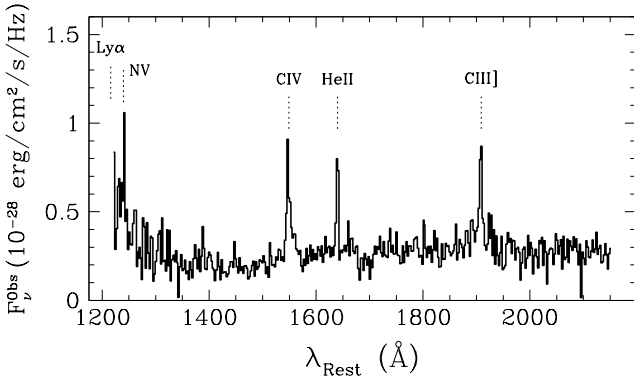
**Table 2**  
Photometry of W0204–0506

Band	Observed $\lambda$ ( $\mu\text{m}$ )	Rest $\lambda$ ( $\mu\text{m}$ )	Magnitude <sup>†</sup>	Flux ( $\mu\text{Jy}$ )	Telescope/Instrument	Ref
$g'$	0.46	0.15	22.94 (0.05)	2.4 (0.1)	MMT/Megacam	(1)
$r'$	0.61	0.20	22.53 (0.06)	3.5 (0.2)	MMT/Megacam	(1)
$i'$	0.75	0.24	22.09 (0.09)	5.2 (0.4)	MMT/Megacam	(1)
$z'$	0.89	0.29	21.69 (0.06)	7.4 (0.4)	MMT/Megacam	(1)
$u$	0.35	0.13	23.00 (0.60)	2.2 (1.3)	SDSS	(2)
$g$	0.46	0.15	22.66 (0.17)	3.1 (0.5)	SDSS	(2)
$r$	0.61	0.20	22.49 (0.23)	3.6 (0.8)	SDSS	(2)
$i$	0.75	0.24	21.80 (0.18)	6.9 (1.2)	SDSS	(2)
$z$	0.89	0.29	22.03 (0.67)	4.3 (4.3)	SDSS	(2)
$r$	0.62	0.20	22.36 (0.17)	4.1 (0.6)	SOAR/SOI	(3)
$J$	1.2	0.40	20.77 (0.22)	8.0 (1.6)	WIYN/WHIRC	(4)
[3.6]	3.6	1.15	17.18 (0.05)	37.2 (1.9)	<i>Spitzer</i> /IRAC	(5)
[4.5]	4.5	1.45	16.34 (0.03)	52.2 (2.6)	<i>Spitzer</i> /IRAC	(5)
W1	3.4	1.06	17.34 (0.12)	35.4 (3.8)	WISE	(6)
W2	4.6	1.47	16.10 (0.16)	61.8 (9.0)	WISE	(6)
W3 <sup>‡</sup>	12	3.41	10.25 (0.06)	2714 (140)	WISE	(6)
W4 <sup>‡</sup>	22	7.07	7.07 (0.09)	11414 (946)	WISE	(6)
P70	70	22.58	...	71000 (3000)	<i>Herschel</i> /PACS	(7)
P160	160	54.84	...	113000 (5000)	<i>Herschel</i> /PACS	(7)
S250	250	80.65	...	46000 (11000)	<i>Herschel</i> /SPIRE	(7)
S350	350	112.90	...	27000 (11000)	<i>Herschel</i> /SPIRE	(7)
S500	500	161.29	...	17000 (15000)	<i>Herschel</i> /SPIRE	(7)

**Note.** — References: (1) Finkelstein et al. (2007); (2) Ahn et al. (2014); (3) Eisenhardt et al. (in prep.); (4) Assef et al. (2015); (5) Griffith et al. (2012); (6) Wright et al. (2010); (7) Tsai et al. (2015)

<sup>†</sup> Magnitudes are presented in their standard photometric system, namely AB for  $g'r'i'z'$  and *ugriz*, and Vega for the rest. For the SDSS bands we present *asinh* magnitudes, while we present Pogson magnitudes for all others.

<sup>‡</sup> As discussed in §2, we have corrected the W3 and W4 fluxes according to the prescription suggested by Wright et al. (2010) for objects with red WISE colors.



**Figure 2.** Gemini South/GMOS-S optical spectrum of W0204–0506, binned in wavelength by a factor of 8 for clarity. The dotted vertical lines show the wavelength of the Ly $\alpha$ , NV, CIV, HeII and CIII] emission lines. The detected emission lines yield a redshift of  $z = 2.100$ .

comparing *Spitzer* imaging of Hot DOGs to those of radio galaxies as reported by Wylezalek et al. (2013), Assef et al. (2015) showed that Hot DOGs reside in similarly overdense environments, suggestive of high-redshift proto-clusters in the process of formation.

Combining the redshift with the *Spitzer*, WISE and *Herschel* observations we estimate an infrared luminosity of  $L_{\text{IR}} = 4.4 \times 10^{13} L_{\odot}$  using the approach of Tsai et al. (2015), which puts W0204–0506 well into the HyLIRG category. W0204–0506 is not detected by the VLA FIRST survey at 1.4 GHz, with a catalog detection

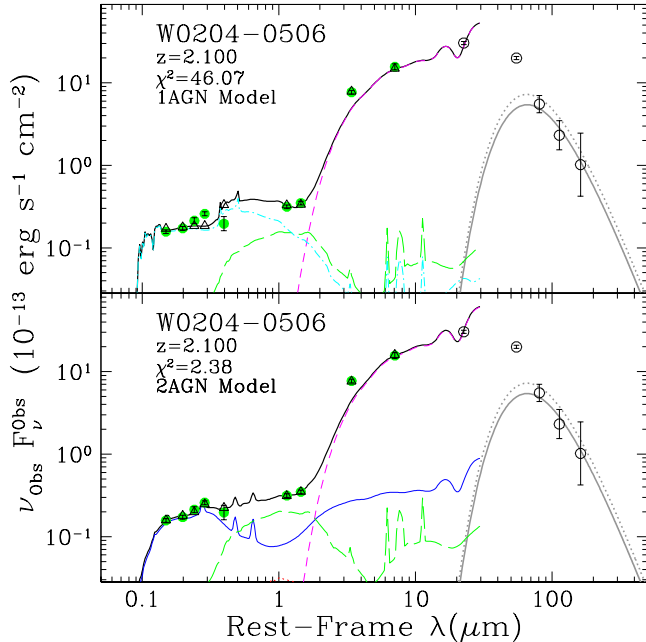
limit of 1 mJy/beam. Assuming the object is a point source, this translates into a specific luminosity limit of  $L_{\nu}(4.34 \text{ GHz}) < 9.7 \times 10^{31} \text{ erg s}^{-1} \text{ Hz}^{-1}$  and a limiting flux density ratio between rest-frame 4.34 GHz and rest-frame 4400Å of  $f_{\nu}(4.34 \text{ GHz})/f_{\nu}(4400\text{Å}) < 1000$ , neither of which is stringent enough to classify W0204–0506 as radio-loud nor confirm it as radio-quiet (Stern et al. 2000).

### 3.2. SED Modeling

The top panel of Figure 3 shows the best-fit “1AGN” model to the UV-through-mid-IR photometry of W0204–0506. The fit to the optical photometry is poor, as reflected by the large value of  $\chi^2 = 46.07$  with only four degrees of freedom for the fit ( $\chi^2_{\nu} = 11.5$ ). The bottom panel of this Figure shows the best-fit “2AGN” model, which provides a significantly better  $\chi^2$  value of 2.38 ( $\chi^2_{\nu} = 1.2$ ). Comparing both models through an F-test yields  $P_{\text{Ran}} = 5 \times 10^{-2}$ , implying that the addition of a secondary unobscured AGN component is justified (see discussion in §1). The best-fit “2AGN” model consists of a highly obscured luminous AGN that dominates the infrared luminosity with  $E(B - V) = 9.7 \pm 1.2$  and a  $6\mu\text{m}$  luminosity of  $L_{6\mu\text{m}} = 1.9 \pm 0.2 \times 10^{13} L_{\odot}$ . The rest-frame UV/optical is, on the other hand, dominated by a lightly reddened AGN component with  $E(B - V) = 0.13 \pm 0.02$  and a significantly lower  $6\mu\text{m}$  luminosity of  $L_{6\mu\text{m}} = 2.7 \pm 0.5 \times 10^{11} L_{\odot}$ , of order 1% of the luminosity of the highly obscured AGN.

SED modeling can also allow us to constrain the stel-





**Figure 3.** UV through mid-IR SED of W0204-0506. The solid green circles, open triangles, solid black line and color lines have the same meaning as in Fig. 1. The top and bottom panels show the best-fit “1AGN” and “2AGN” models to the SED (see §2 for details). The “2AGN” model clearly provides a better description of the observed flux densities. The open circles show the flux densities of W0204-0506 in the *Herschel* band; these were not used in the SED modeling. The solid gray line shows the best-fit modified blackbody (assuming  $\beta = 1.5$  and  $T = 40$  K; see §5.3 for details) to the three longer wavelength (SPIRE) bands. The dotted gray line shows the same but with a luminosity at the 90% confidence limit above that of the best-fit.

lar mass of this object. Unfortunately, we do not have enough information to constrain the  $M/L$  ratio, so instead we use the approach of Assef et al. (2015) and estimate an upper bound. The maximal stellar mass estimate analysis for Hot DOGs done by Assef et al. (2015) yields  $M_{*}^{\text{Max}} = 7 \times 10^{11} M_{\odot}$  for this object, assuming the “1AGN” model. The “2AGN” best-fit will yield a lower upper-bound on the stellar mass, as the rest-frame  $K$ -band luminosity is less dominated by the stellar emission, so we use the estimate of the “1AGN” model as it is the most conservative upper-bound.

While the “2AGN” model fits the data very well, we cannot immediately interpret this as proving the existence of the secondary unobscured AGN component in the SED of W0204-0506 expected for the dual AGN and reflection scenarios. Instead, the blue excess emission may be described by an extremely luminous and young starburst, as described in §2, which falls beyond the parameter space covered by the empirical host galaxy templates we considered. In the next section we study the deep X-ray observations available for this object to gain further insight into the nature of the unusual SED of W0204-0506.

#### 4. X-RAY OBSERVATIONS OF W0204-0506

W0204-0506 was serendipitously observed by the *Chandra X-ray Observatory* as part of the LALA Cetus field observations (PID: 04700805, PI: Malhotra) presented by Wang et al. (2007). The field was observed

during Cycle 4 with the ACIS-I (Garmire et al. 2003) instrument for 160 ks starting on UT 2003 June 13 and then again for 15 ks more starting on UT 2003 June 15. For simplicity we only use the 160 ks observation. The *Chandra* observation was taken in the Timed Event mode, and we extracted spectra from the ACIS-I detector using the standard pipeline in CIAO v4.6<sup>15</sup>. The source spectrum was obtained from a circular region of radius  $\sim 2''$ , while the background was extracted from a larger nearby circular region that was free from any other contaminating sources. The source is detected with 94 counts and is visually consistent with a point source. Owing to the low count statistics, the source spectrum was only lightly grouped with a minimum of 1 count per bin. We therefore carry out the parameter estimation by minimizing the Cash statistic (Cash 1979), modified through the W-statistic provided by XSPEC<sup>16</sup> to account for the subtracted background.

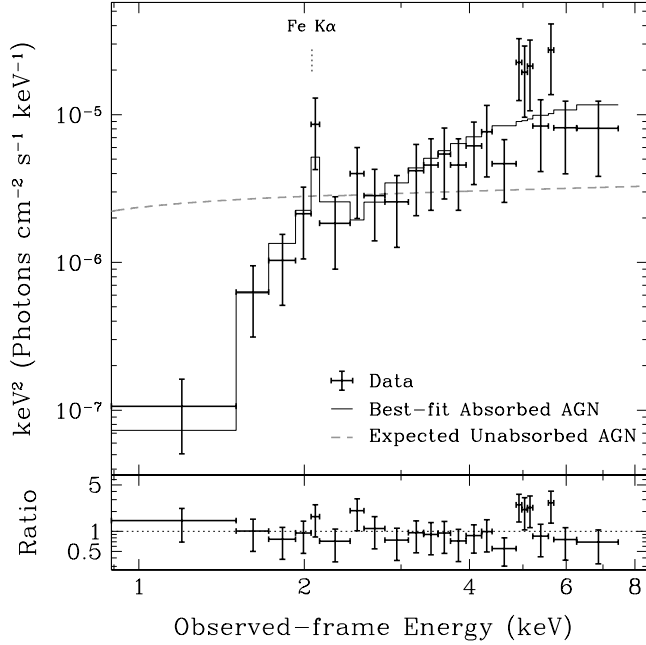
Figure 4 shows the unfolded spectrum from the *Chandra* observations. The emission is clearly hard, implying it is powered by a highly absorbed AGN, as expected from the multi-wavelength SED presented in the previous section. While the Figure may show a tentative Fe  $K\alpha$  line, the counts are too low to determine whether the line is real or simply a statistical fluctuation. The Figure also shows the best-fit absorbed AGN obtained using the models of Brightman & Nandra (2011). These models predict the X-ray spectrum as observed through an optically thick medium with a toroidal geometry, as posited by the AGN unified scheme. The models employ Monte-Carlo techniques to simulate the transfer of X-ray photons through the optically-thick neutral medium, self-consistently including the effects of photoelectric absorption, Compton scattering and fluorescence from Fe K, amongst other elements. Treating these effects self-consistently rather than separately has the advantage of reducing the number of free parameters and of gaining constraints on the spectral parameters. It is therefore particularly useful for low count spectra such as the one we are fitting here.

The best-fit model yields a photon-index of  $\Gamma = 1.6_{-0.0}^{+0.8}$ , a neutral hydrogen column density of  $N_{\text{H}} = 6.3_{-2.1}^{+8.1} \times 10^{23} \text{ cm}^{-2}$  and an absorption-corrected 2–10 keV luminosity of  $\log L_{2-10\text{keV}}/\text{erg s}^{-1} = 44.9_{-0.14}^{+0.86}$ . The best-fit model has a Cash statistic of  $C = 66.08$  for 77 degrees of freedom. The uncertainties quoted correspond to the 90% confidence interval. Note that the photon-index is poorly constrained by the data, so we require  $\Gamma \geq 1.6$  since lower values of the photon-index are only observed in SMBHs accreting at low Eddington rates (e.g., Shemmer et al. 2006, 2008; Risaliti et al. 2009; Brightman et al. 2013).

The properties derived for the luminous, highly absorbed AGN emission dominating the X-rays are in good agreement with those derived for the luminous, highly obscured AGN component that dominates the IR SED. Assuming the median dust-to-gas ratio observed by Maiolino et al. (2001) in AGN, namely  $E(B - V)/N_{\text{H}} = 1.5 \times 10^{-23} \text{ cm}^2 \text{ mag}$ , the best-fit accretion disk obscuration found through the SED modeling for the highly

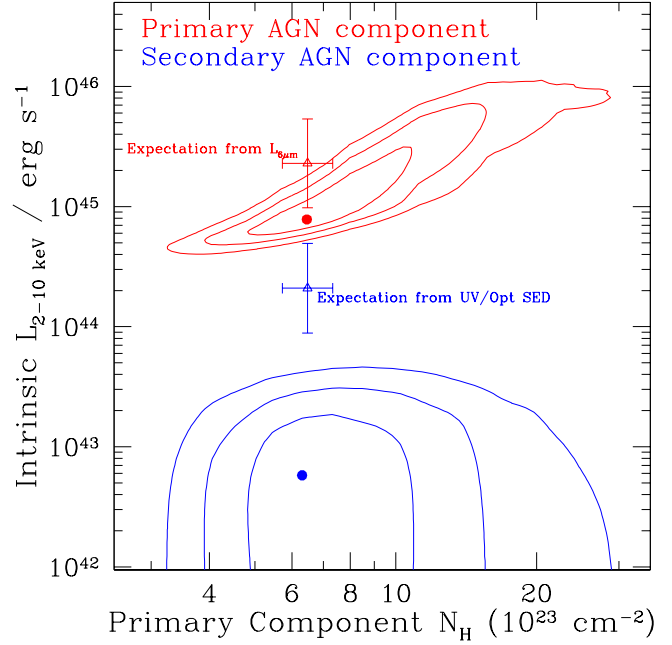
<sup>15</sup> <http://cxc.harvard.edu/ciao/>

<sup>16</sup> <https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixStatistics>



**Figure 4.** (Top) The black crosses show the binned, unfolded *Chandra*/ACIS-I spectrum of W0204-0506 from the LALA field observations of Wang et al. (2007). The data have been rebinned here for visual purposes only. The solid black histogram shows the best-fit absorbed AGN using the models of Brightman & Nandra (2011). The dashed gray line shows the spectrum expected for the lightly obscured AGN component suggested by the excess blue emission of W0204-0506. (Bottom) Flux ratio between the observations and the best-fit absorbed AGN.

obscured AGN corresponds to a neutral hydrogen column density of  $N_H = 6.5 \pm 0.8 \times 10^{23} \text{ cm}^{-2}$ , a value which is consistent with that measured from the X-ray spectrum. Similarly, we can compare the estimated luminosities, as the intrinsic  $L_{2-10\text{keV}}$  luminosity of an AGN correlates well, although with considerable scatter, with its monochromatic luminosity at  $6\mu\text{m}$ ,  $L_{6\mu\text{m}}$  (e.g., Fiore et al. 2009; Gandhi et al. 2009; Bauer et al. 2010; Mateos et al. 2015; Stern 2015). These relations are typically linear (with the exception of Fiore et al. 2009, who used a broken power-law) and have been derived for limited energy regimes, but Stern (2015) has recently shown that a quadratic relation does a better job at describing the entire AGN luminosity range. In particular, this relation has been derived considering objects with luminosities as high as those of Hot DOGs, making it the most appropriate one to use in this context. From the relation presented by Stern (2015), adding its scatter of 0.37 dex to the uncertainty budget, we get that the best-fit  $L_{6\mu\text{m}}$  for the highly obscured, luminous AGN component corresponds to an intrinsic X-ray luminosity of  $\log L_{2-10\text{keV}}/\text{erg s}^{-1} = 45.36 \pm 0.37$ , which is consistent with the estimate from the X-ray spectrum. Figure 5 shows the confidence contours for  $\log L_{2-10\text{keV}}$  and  $N_H$  obtained from the multi-wavelength SED described above. The latter are consistent with the X-ray spectrum estimates, although the agreement is better once the scatter of the  $L_{2-10\text{keV}} - L_{6\mu\text{m}}$  is taken into account. This consistency implies that the same AGN component is responsible for both the IR SED and the X-ray emis-



**Figure 5.** Confidence intervals of the joint fit of the two AGN components to the *Chandra*/ACIS-I spectrum as described in the text. The red lines show the 1, 2 and  $3\sigma$  confidence contours of the best-fit  $L_{2-10\text{keV}}$  and  $N_H$  parameters for the primary (i.e., highly luminous, highly absorbed) AGN component. The photon-index,  $\Gamma$  was also fit for this component. The blue lines show the 1, 2 and  $3\sigma$  confidence contours of the best-fit  $L_{2-10\text{keV}}$  of the secondary (i.e., less luminous, lightly absorbed) AGN component as a function of the  $N_H$  of the primary AGN component. The  $N_H$  and  $\Gamma$  of the secondary component were fixed to  $8.9 \times 10^{21} \text{ cm}^{-2}$  and to 1.9 respectively, as described in the text. The red and blue open triangles show expected values obtained from the best-fit “2AGN” model as described in the text.

sion, as expected.

In §2 we suggested three mechanisms to explain the blue excess component that dominates the rest-frame UV/optical SED of BHDs. For the presence of a secondary active SMBH with little or no obscuration, we would expect to see the corresponding unabsorbed/lightly absorbed X-ray emission. However, the X-ray spectrum in Figure 4 is strongly inconsistent with the presence of an additional AGN component with little or no absorption. If we use the  $L_{6\mu\text{m}} - L_{2-10\text{keV}}$  relation of Stern (2015), we find that the corresponding X-ray luminosity for the secondary AGN that best-fits the rest-frame UV/optical SED would be  $\log L_{2-10\text{keV}}/\text{erg s}^{-1} = 44.32 \pm 0.37$ . Assuming the median gas-to-dust ratio of Maiolino et al. (2001), the best-fit obscuration of  $E(B - V) = 0.13$  corresponds to a low absorption of  $N_H = 8.9 \times 10^{21} \text{ cm}^{-2}$ ; such a component would have significant power at soft energies. Figure 4 shows the expected X-ray signal from a power-law spectrum with the above luminosity and a photon-index  $\Gamma = 1.9$  under this light amount of absorption in comparison to the observed X-ray spectrum, illustrating that the observations are highly inconsistent. If we allow for the luminosity of this component to be fit to the spectrum (keeping  $N_H$  and  $\Gamma$  fixed) simultaneously with the parameters for the heavily absorbed power-law described earlier, we find that with 90% confidence  $\log L_{2-10\text{keV}}/\text{erg s}^{-1} < 43.3$ ,



over an order magnitude below the expectation from the luminosity of the component that dominates the rest-frame UV/optical SED. Figure 5 shows the confidence intervals for the luminosity of this component as well as the expectation from the UV/optical SED signal. The confidence intervals for the primary component are qualitatively unaffected by the additional unobscured component and hence are not shown. Fixing the X-ray luminosity of the component to the expected value of  $\log L_{2-10\text{keV}}/\text{erg s}^{-1} = 44.32$  yields a Cash statistic of  $C = 194.46$ . This implies a  $\Delta C = 128.38$  above the best-fit, which means we can rule this scenario out with  $> 99.9\%$  confidence.

## 5. THE ORIGIN OF THE BLUE EXCESS EMISSION IN W0204-0506

As stated in §2, there are three scenarios that can naturally explain the SED of W0204-0506. Below we discuss each of them in light of the observations described in the previous sections.

### 5.1. Leaked AGN Light

As discussed in §2, a source for the blue, AGN-like rest-frame UV/optical SED could be that the UV emission from the hyper-luminous, highly obscured AGN that powers the infrared emission of W0204-0506 is leaking out from the inner regions of the galaxy. This could happen, in principle, from scattering of the central engine light by free electrons, or by reflection on dust grains. The fraction of the emitted flux from the obscured central engine that is leaking into our line of sight in the UV/optical would be of order 1%, as that is the relative luminosity found by the SED modeling between the intrinsic luminosity estimated for the AGN powering the rest-frame UV/optical to that needed to power the IR emission. The cross section for scattering by either free electrons or by dust grains, however, is significantly smaller in the energy range of our ACIS-I spectrum than in the UV (Draine 2003a,b), so the lack of a luminous soft X-ray component found in §4 is consistent with this scenario. This makes the reflection the most likely scenario we review, although we note that this simple estimate neglects a dependence of reflection on wavelength across the SED. For reflection off dust grains, such an effect depends on the specific properties of the dust grains and on the geometry of the dust with respect to SMBH, but full modeling of it falls well beyond the scope of this paper.

An alternative method for the emission to escape from the hyper-luminous, highly obscured AGN would be to simply have a partially unobscured line-of-sight towards the accretion disk, such that 1% of the emission is reaching us directly. The fact that we see emission consistent with a lightly obscured accretion disk up to the Lyman-break already makes this unlikely. The partial coverage would have to allow a direct line of sight to 1% of the accretion disk at all wavelengths, despite the rest-frame UV coming primarily from regions closer in to the BH than the longer optical wavelengths (Shakura & Sunyaev 1973; Kochanek 2004; Anguita et al. 2008), and from a physically distinct region than the X-rays (Vaiana & Rosner 1978; Haardt & Maraschi 1993). Figure 5 shows that the X-ray data cannot rule out a secondary unobscured AGN component with 1% the X-ray luminosity of the obscured

component, as would be expected for this partial obscuration scenario. Furthermore, it is not necessary for the gas and dust distribution to trace each other perfectly (see, e.g., Merloni et al. 2014). Nonetheless, the complex dust geometry that would be necessary to obtain the observed SED in this scenario makes it unlikely.

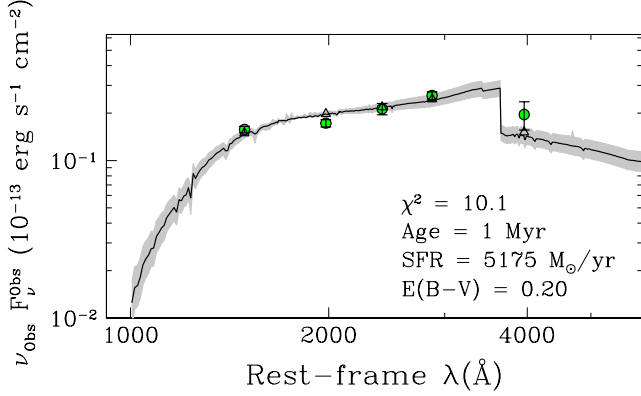
### 5.2. Dual Quasar

Alternatively, the unobscured AGN emission in the rest-frame UV/optical SED could be from an independent accreting SMBH, making W0204-0506 a dual quasar system. Dual AGN are rare objects, but there are several confirmed cases in the literature (e.g. Komossa et al. 2003; Hudson et al. 2006; Bianchi et al. 2008; Koss et al. 2011b; Fu et al. 2011; Comerford et al. 2011; Liu et al. 2013). Furthermore, this scenario might *a priori* be plausible, as hyper-luminous AGN activity phases such as those in Hot DOGs might be triggered by major galaxy mergers (e.g., Hopkins et al. 2008). This scenario is, however, inconsistent with the lack of a lightly absorbed AGN component at the expected luminosity in the X-ray spectrum, as discussed in §4. This scenario could fit the observations if the secondary, lightly obscured AGN was intrinsically X-ray weak (Luo et al. 2013, 2014; Teng et al. 2014), but all such objects identified to date are broad absorption line (BAL) QSOs, and we do not see any trace of BAL features in the optical spectra (see Fig. 2). Recently Teng et al. (submitted) has pointed out that AGN in ULIRGs may be potentially X-ray weak too, although it is hard to tell how much of a role obscuration plays in these objects. Hence, while we cannot completely rule out the dual quasar scenario, we consider it unlikely given the ACIS-I observations presented here.

### 5.3. Extreme Star-Formation

It is possible that the UV/optical excess observed in BHDs is not due to accretion onto an SMBH, but to intense, unobscured star-formation. Over the first  $\sim 100$  Myr, a pure starburst has a UV/optical SED rising strongly towards the blue, up to the Lyman break. This is similar to the SED of unobscured QSOs. Hence, it is possible to model the SED of W0204-0506 as a mildly obscured young starburst instead of as a mildly obscured AGN in §3. Detailed modeling is not feasible with the low number of photometric bands available for W0204-0506 in the rest-frame UV/optical, so we concentrate here in determining the lowest possible amount of star-formation that would be needed to power its UV/optical SED. We use SED models generated with the Starburst99 v7.0.0 code (Leitherer et al. 1999, 2010, 2014; Vázquez & Leitherer 2005) in combination with the *EzGal* package of Mancone & Gonzalez (2012), and take the following approach.

For W0204-0506,  $J$ -band corresponds to rest-frame  $4000\text{\AA}$ , so its blue  $z' - J$  color precludes the presence of a strong Balmer-break, implying a very young age for the starburst. We assume models with a constant SFR generated by Starburst99, although our results are qualitatively similar if we instead use a simple stellar population. We assume the latest Geneva models available for this version of Starburst99 (see Leitherer et al. 2014, for details). Since the  $g' - r'$  color is significantly redder than would be expected for a young starburst, we

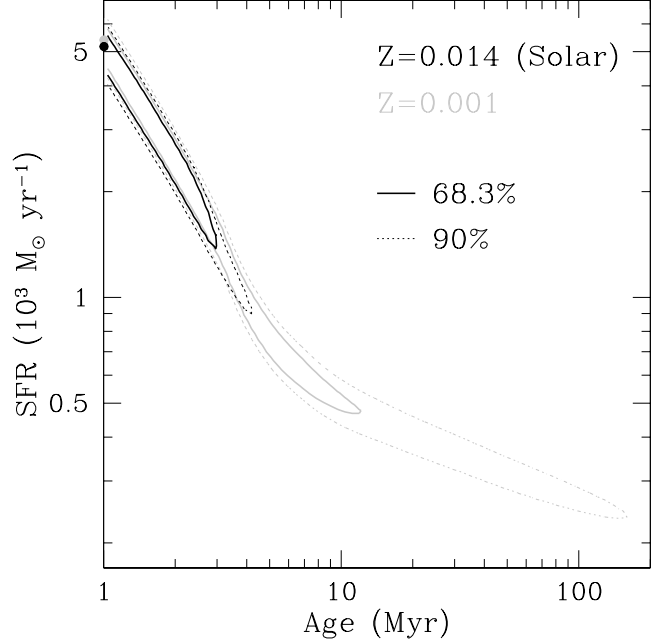


**Figure 6.** The solid black line shows the best-fit SED model from Starburst99 to the  $g'$ ,  $r'$ ,  $i'$ ,  $z'$  and  $J$  band flux densities (solid green circles). The expected flux densities from the best-fit model are shown by the open triangles, and its physical parameters are given in the legend. The gray region shows all SED shapes within the 90% confidence interval.

also allow for obscuration to be fit to this component, assuming the same reddening-law as in §3. Assuming a reddening law with a strong 2175Å feature, as is observed in the Milky Way (e.g., Cardelli et al. 1989), results in a poorer description of the SED. The large amount of dust present in the system is indicative of a considerable mean metallicity, so we assume a solar metallicity for our models, although we discuss the effects of this choice later in this section. We assume a Salpeter initial mass function (IMF; Salpeter 1955) with mass ranges between  $0.08 M_{\odot}$  and  $120 M_{\odot}$ . For the rest of the input parameters of the Starburst99 code we assume the standard recommended options.

Figure 6 shows the best-fit SED to the observed UV/optical SED. When fitting the SED, we impose a minimum age of 1 Myr and find the best-fit model has  $\chi^2 = 10.1$ , with an age of 1 Myr,  $E(B - V) = 0.20$  and  $\text{SFR} = 5200 M_{\odot} \text{ yr}^{-1}$ . Note that the fit is much poorer than for the AGN model, particularly as we only consider five data points. As we fit for the amplitude, reddening and age, this implies  $\chi^2_{\nu} = 10.1/2 = 5.05$ . If we lift the minimum age requirement we find the best-fit SED requires an enormous SFR of approximately  $50,000 M_{\odot} \text{ yr}^{-1}$  but with an almost indistinguishable  $\chi^2 = 9.9$ . This implies there is a strong degeneracy between age and SFR in our models, which is made clearer by the contours shown in Figure 7. Considering this degeneracy, we can determine that, with 90% confidence,  $\text{SFR} \gtrsim 1000 M_{\odot} \text{ yr}^{-1}$ . While  $\text{SFR} > 1000 M_{\odot} \text{ yr}^{-1}$  is routinely observed in SMGs and ULIRGS (e.g., Barger et al. 2014), it is always heavily dust obscured and hence only detected in the far-IR. Barger et al. (2014) shows, based on the measurements of van der Burg et al. (2010), that UV measured SFRs in Lyman break galaxies at  $z > 3$  cut off at  $\sim 300 M_{\odot} \text{ yr}^{-1}$ , suggesting that an unobscured  $\text{SFR}_{\text{Min}} \sim 1000 M_{\odot} \text{ yr}^{-1}$  is very unlikely.

A somewhat better fit to the data can be obtained by assuming a lower metallicity. If we consider the lowest possible metallicity provided for the Geneva models by Starburst99, namely  $Z = 0.001$ , we find that the best-fit SED has  $\chi^2 = 7.8$  ( $\chi^2_{\nu} = 3.9$ ) and  $\text{SFR} = 5400 M_{\odot} \text{ yr}^{-1}$ . Yet, as shown in Figure 7, this significantly relaxes



**Figure 7.** The contours show a  $\chi^2$  map of the best-fit SED models of Starburst99 to the  $g'$ ,  $r'$ ,  $i'$ ,  $z'$  and  $J$  band flux densities for a fixed age and SFR of the starburst (see §5.3 for details of the SED modeling). The contours for the model assuming a solar metallicity ( $Z = 0.014$ ) are shown in black while the contours for the model assuming  $Z = 0.001$  are shown in gray. The solid (dotted) contour shows the 68.3% (90%) confidence region. The solid dots show the best-fit models (see Fig. 6).

the requirement on the minimum SFR, implying only  $\text{SFR} \gtrsim 250 M_{\odot} \text{ yr}^{-1}$  with 90% confidence. This would be consistent with the upper envelope of what has been found for Lyman break galaxies. However this model would require that the gas feeding the starburst has far lower metallicity than that feeding and surrounding the nucleus, so we do not consider it any further.

Note that we have not included the WISE W1 band flux to constrain these fits despite the fact that W1 would be dominated by the host galaxy emission if the blue-excess is due to star-formation (see Fig. 3). Adding the W1 flux as a constraint results in a much poorer fit by our constant SFR model ( $\chi^2 = 28$ ) that severely underestimates the observed W1 flux. This is not surprising, as it simply highlights the need for an older stellar population in the system. However, it is worth noting that adding an older stellar component would only make the best-fit SFR larger and the starburst younger, as it would imply an even stronger inverse Balmer-break for the starburst. Nevertheless, we expect the changes to be negligible based on the W1 amplitude and the large  $J$ -band flux uncertainty.

An independent constraint on the SFR can be obtained from *Herschel*/SPIRE observations of W0204-0506, as the cold dust emission from star-forming regions is a good tracer of their activity (e.g. Kennicutt 1998). As discussed by previous studies (Eisenhardt et al. 2012; Wu et al. 2012, 2014; Jones et al. 2014; Tsai et al. 2015), the far-IR SEDs of Hot DOGs are dominated by the hot dust emission powered by the AGN, and show no evidence for a significant cold component associated

with star-formation. Assuming that the *Herschel*/SPIRE fluxes of W0204–0506 are powered solely by star formation, we can thus place a conservative limit on the SFR. We fit the 250, 350 and 500  $\mu\text{m}$  fluxes with a modified blackbody and then estimate the SFR limit using the  $L_{\text{FIR}} - \text{SFR}$  relation of Kennicutt (1998), assuming a Salpeter IMF. We assume  $\beta = 1.5$  and a dust temperature of  $T = 40$  K for the modified blackbody, similar to what was done by Wu et al. (2012) to fit ground-based submm observations of Hot DOGs. This temperature is chosen as it is representative of the hottest dust emission associated with star formation (Magnelli et al. 2012); lower temperatures will result in lower SFR estimates. The best-fit modified black-body, shown by the solid gray line in Figure 3, yields  $\text{SFR}_{\text{IR}}^{\text{Lim}} = 2500 \pm 500 \text{ M}_{\odot} \text{ yr}^{-1}$  if we assume the limit case where all luminosity of this component is powered by star-formation. Using the 90% confidence level, shown by the dotted gray line in Figure 3, we can place the conservative limit of  $\text{SFR}_{\text{IR}} < 3350 \text{ M}_{\odot} \text{ yr}^{-1}$ .

Considering the lower limit derived earlier from the optical SED of  $\text{SFR}_{\text{Min}} \gtrsim 1000 \text{ M}_{\odot} \text{ yr}^{-1}$ , we conclude it is possible that the UV/optical SED is powered by star-formation. However, we consider it less likely than the reflection scenario because a) the SED fit is much poorer than with our 2AGN model, and b) as discussed earlier, it would be a level of unobscured star-formation that has not been observed before (Barger et al. 2014). If the UV/optical SED is dominated by star-formation, the upper bound on the stellar mass of  $M_{*}^{\text{Max}} = 7 \times 10^{11} \text{ M}_{\odot}$  combined with the lower bound on SFR of  $10^3 \text{ M}_{\odot} \text{ yr}^{-1}$  implies a specific star formation rate  $> 1.4 \times 10^{-9} \text{ yr}^{-1}$ , i.e., that the host galaxy would be doubling its stellar mass in a timescale shorter than 700 Myr.

For completeness, we also estimate the maximum star formation rate allowed by the X-ray data in addition to the primary AGN component. We used the relation between SFR and integrated 0.5–8 keV X-ray luminosity outlined in Mineo et al. (2014):  $L_{\text{X}}/\text{SFR} = 4 \times 10^{39} (\text{erg s}^{-1})/(\text{M}_{\odot} \text{ yr}^{-1})$ . These authors found the total 0.5–8 keV X-ray emission from star formation was  $\sim 2/3$  from X-ray binaries (XRBs), and  $\sim 1/3$  from diffuse plasma emission from the ISM. For the plasma emission, we adopted a Mekal plasma model (Mewe et al. 1985) with a rest-frame temperature set to 0.25 keV (the average found by Mineo et al. 2012). Additionally, at the star formation rates relevant here, we assumed that the integrated spectrum from the XRB would be dominated by ultraluminous X-ray sources (ULXs; Feng & Soria 2011, for a recent review), and adopted a simple model based on recent *NuSTAR* observations of ULXs (Bachetti et al. 2013; Walton et al. 2013, 2014, 2015a,b; Rana et al. 2015; Mukherjee et al. 2015), approximating the spectrum with a cutoff powerlaw model with  $\Gamma = 1.5$  and  $E_{\text{cut}} = 7$  keV, scaled to  $z = 2.1$ . Both components are then modified by the neutral absorption column of  $1.3 \times 10^{22} \text{ cm}^{-2}$  indicated by the optical emission (also assumed to be at  $z = 2.1$ ). Setting the XRB and diffuse plasma contributions to  $2/3$  and  $1/3$  of the total SFR X-ray emission in the rest-frame 0.5–8 keV bandpass, respectively, and allowing the total emission to vary, we obtain a 90% upper limit of  $\sim 5500 \text{ M}_{\odot} \text{ yr}^{-1}$ , somewhat less constraining than, but consistent with, the

upper limit obtained from the *Herschel* observations. We also note for completeness that the star-formation constraints from the FIRST radio observations are poorer than for the X-rays, as the upper bound of 1 mJy at observed 1.4 GHz flux implies  $\text{SFR}_{1.4 \text{ GHz}} < 7600 \text{ M}_{\odot} \text{ yr}^{-1}$  according to the relation of Murphy et al. (2011) and assuming  $F_{\nu} \propto \nu^{-0.2}$ .

## 6. CONCLUSIONS

We have introduced an interesting subsample of Hot DOGs that show UV/optical broad-band emission significantly in excess of what is typically expected for star formation. Based on UV through mid-IR photometry and spectroscopy for a large sample of objects, we find that BHDs constitute  $\sim 8\%$  of Hot DOGs, although this number is considerably uncertain due to the complex selection function.

We argue that the blue excess can most naturally be explained by three different scenarios, namely: (i) light leaked from the hyper-luminous, highly obscured AGN that dominates the IR emission, either by reflection off dust grains or free electrons, or by an opening between dust clouds allowing a direct line-of-sight to a fraction of the accretion disk; (ii) a second, less luminous and largely unobscured AGN in the system; or (iii) a young massive coeval starburst. While our current data does not allow us to generally differentiate between these scenarios in most objects, we argue additional observations can help disentangle them. In particular we note that the detection of rest-frame UV/optical variability could confirm the AGN nature of the blue excess, and that spectropolarimetry could confirm the reflection scenario. Similarly, high spatial resolution UV/optical imaging could identify the two nuclei of a dual AGN, or confirm the presence of a galaxy-wide massive young starburst. We also argue that X-ray observations would allow us to at least partially differentiate between these scenarios with some confidence. One of the BHDs found on this article, namely W0204–0506, was serendipitously imaged in the *Chandra*/ACIS-I 174.5 ks observations of the LALA field by Wang et al. (2007), and we use these data to analyze the different scenarios outlined above. With this depth, W0204–0506 is the Hot DOG with the best X-ray coverage to date.

We find that the X-ray spectrum of W0204–0506 is dominated by the higher energy emission. Of the 94 photons detected in the 0.3–8 keV energy range, 80 have energies between 2 and 8 keV. Using the models of Brightman & Nandra (2011), we find that the X-ray spectrum is well fit by an absorbed AGN with  $\Gamma = 1.6_{-0.0}^{+0.8}$ ,  $N_{\text{H}} = 6.3_{-2.1}^{+8.1} \times 10^{23} \text{ cm}^{-2}$  and an intrinsic luminosity of  $\log L_{2-10\text{keV}}/\text{erg s}^{-1} = 44.9_{-0.14}^{+0.86}$ . We show that the values of  $N_{\text{H}}$  and  $\log L_{2-10\text{keV}}$  are consistent with those expected from the IR properties of the AGN through correlations established in the literature.

Furthermore, we find that the ACIS-I observations strongly limit the contribution from a hypothetical secondary, lightly absorbed AGN, and show that a component consistent with the AGN derived from the UV/optical SED is ruled out with  $> 99.9\%$  confidence. Hence, we conclude that the excess blue emission in W0204–0506 is highly unlikely to be contributed by a secondary, less luminous AGN in the system. The lack

of detection of a secondary component in the X-rays is consistent with the scenario of a single partially-covered AGN, but leaked AGN light due to partial coverage implies an unlikely dust geometry, and we consider reflected light from a single AGN to be a more likely explanation. The X-ray observations are also consistent with an extreme, coeval starburst. Using observations from *Herschel*/SPIRE, we show that the IR emission puts a robust upper limit of  $\text{SFR}_{\text{IR}} < 3350 \text{ M}_{\odot} \text{ yr}^{-1}$ , while the rest-frame UV/optical SED requires  $\text{SFR} \gtrsim 1000 \text{ M}_{\odot} \text{ yr}^{-1}$  to be powered by the star formation, showing that it is possible the UV/optical emission is powered by star-formation. However, we consider this scenario less likely than the reflection one because a) the fit to the optical data is much worse than for the AGN model, and b) the required unobscured SFR would be much larger than the highest observed in Lyman-break galaxies (Barger et al. 2014). Hence, the reflection scenario either by dust grains or free electrons is the most likely one to explain the nature of the blue excess in W0204–0506, although key details of the model and an in-depth analysis must be done to fully ascertain its likelihood. Further testing and constraints of this scenario can be obtained through deep spectropolarimetric observations to determine the polarization fraction of the UV/optical emission. Additionally, high-spatial resolution UV/optical imaging can offer insight into whether there is a strong galaxy-wide star-burst or if the excess blue emission is concentrated in the nucleus, as would be expected for the reflection scenario. A recently approved *Chandra*/*HST* observing program (PI: Assef, Proposal ID: 17700696) will obtain X-ray and multi-wavelength UV/optical imaging observations for two additional BHDs, as well as UV/optical imaging for W0204–0506, allowing us to probe this. These two additional BHDs are also being observed as part of an ALMA program aimed at studying the [C II] and far-IR continuum of Hot DOGs (PI: Assef, Proposal ID: 2013.1.00576.S and 2015.1.00612.S). The first results of this program are reported by Diaz-Santos et al. (2015). Additional, high spatial-resolution ALMA observations of the CO emission lines and longer wavelength far-IR continuum in these objects would determine the extension of the possible starburst. The combination of these observations will further probe the nature of these intriguing objects.

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